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WOVEN WIRE PACKINGS

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WOVEN WIRE PACKINGS   ANNUAL REPORT

<u>WOVEN WIRE PACKINGS - ANNUAL REPORT</u>

<u>Jan 1961 - Jan 1962</u>

(1) <u>SUMMARY</u>

A promising modification to the original KnitMesh
Multifil packing has been developed and tested. In this
modification the original spirally-wound mesh arrangement
was replaced by a series of parallel, vertical layers of
mesh. By this arrangement the central region of high
density, which in the original KnitMesh is thought to
cause the severe liquid maldistribution and poor distillation
performance, is removed. At the same time the vertical
layers of mesh, which have been shown to be desirable for
good mass-transfer, are retained.

The Parallel Vertical packing has been tested
at atmospheric pressure and at 200   mm. Hg. absolute
pressure in a six-inches diameter distillation column.
The H.E.T.P. values at atmospheric pressure range from
2 inches at low reflux rates to 5 inches at high rates.
The H.E.T.P. of the original KnitMesh packing is between .
5 and 6 inches. Comparison of modified packing with
other high-efficiency packings on the basis of pressure-
drop per theoretical plate shows that its performance
is superior to all other packings at reflux-rates below
800 lb/hr.ft^2.

The main disadvantage of the Parallel Vertical
packing is the increase of its H.E.T.P. with reflux-rate.
No adequate explanation of this increase is yet available.

A theoretical equation for the liquid spread
in a randomly packed column has been developed. The
equation attempts to take into account the effect of the
column wall on the liquid distribution.

<u>WOVEN WIRE PACKINGS</u>

<u>PART 2</u>   <u>EXPERIMENTAL WORK</u>

(A) <u>Introduction</u>

The main objective of this investigation is the development of a high-efficiency, low pressure-drop woven wire column packing. The present report describes work carried out in the third year of the research.

The previous two years' investigations, which have been described in the Final Technical Status Reports of November 1959 and December 1960, established the following conclusions;

1. The original spirally-wound wire packing produces a poor liquid distribution. A serious concentration of liquid occurs at the axis of the packing.

2. The axial concentration of liquid is thought to result from the high density of the core of the packing, which is caused by the method of assembly of the packing elements.

3. The effect of this liquid maldistribution is to reduce the mass-transfer efficiency of the packing. Thus, a two-foot depth of packing, in which the maldistribution was present over approximately one foot, gave $8\frac{1}{4}$ theoretical plates, whilst a five-foot depth of packing, having about four foot of maldistributed liquid, produced only 12 theoretical plates.

4. Attempts to improve the mass-transfer characteristics of the packing by eliminating the central concentration of liquid were unsuccessful. In one modification the central flow was obstructed by a set of discs placed between packing elements, and in a second modification the vertical packing layers were replaced by horizontal layers. In both cases the liquid distribution was improved, but the distillation performance of the modifications was inferior to that of the original packing.

5. As a result of Conclusion (4), above, it is seen that the bulk liquid distribution is not the only major factor which affects the efficiency of the packing. It is thought that the mechanism of liquid flow over the packing is of importance, and that small-scale spread of liquid takes place better on vertical layers of mesh.

This report describes tests performed on a further, and more successful, modification to the original packing. In this modification the packing is assembled from parallel vertical layers of mesh. By this arrangement the vertical layers of the original packing are retained, but the central high density is removed. In this way the central liquid concentration was destroyed without the use of obstructions.

The parallel vertical packing was assembled by hand for the initial tests. These tests showed the packing to be superior to the original arrangement, and a supply of factory-ma e packing elements was then obtained and tested more thoroughly. Distillation and distribution measurements were made in six-inches diameter columns. The distillation tests were performed at atmospheric pressure and at 200 mm Hg abs.

The performance of this improved packing is compared with other high-efficiency packings.

(B) Initial Tests of Modified KnitMesh Packings

The F.T.S.R. of December 1960 describes the
testing of a number of modifications to the original
KnitMesh Packing. The tests were performed in the six-
inches diameter distribution column, described in F.T.S.R.
Oct. 1959, and the six-inches distillation column described
in F.T.S.R. Dec. 1960. The modifications were designed
principally to remove the central concentration of liquid
observed in the initial distribution experiments with the
original packing. The tests showed that, although the liquid
distribution was improved, the distillation performances
of the modifications was inferior to that of the original
packing.

Two new modifications, described below, were then
tested. They were tested directly in the distillation
column, before their distribution properties had been
measured. By omitting the distribution tests the effec-
tiveness of the modifications could be more quickly
determined.

(i) Cone-Shaped Packing

Previous work has shown that modifications
involving obstructions to the central liquid flow or
horizontal layers of mesh are unsuccessful. A possible
modification which maintains the vertical arrangement of
mesh layers and avoids the use of obstructions, but at
the same time attempts to displace liquid from the core
of the packing, comprises a set of cone-shaped elements
formed from the original spirally-wound elements by pushing
out (along the axis) the central region of the packing.
If the convex cone surface of the element points upwards
there may be a tendency for liquid flowing through the
packing to run from the centre towards the wall, and thereby

reduce the central flow. An advantage of this modification
is that it can be very easily made from the original packing
elements.

This cone-shaped modification was made from the
normal 8-stand Multifil Copper KnitMesh sections by deforming
the elements to give a cone angle, measured between the
axis and the sloping face of the cone of 45°. Displacement
of liquid towards the wall will be greatest when adjacent
packing elements are not in contact, and so spacers were
placed between adjacent sections. The spacers consisted
of four metal limbs of $\frac{1}{4}$ - inch depth joined to each other
at one of their ends to form the skeleton of a cone whose
apex is the point of interconnection of the limbs.

The packing was tested in the six-inches diameter
distillation column described in F.T.S.R. Dec. 1960.
Five packing elements were loaded into the column to
give a packed depth of 2 foot measured from the base of
the bottom element to the apex of the top packing element.

(ii) Parallel Vertical Packing

A second modification, in which vertical layers
of mesh are used and which avoids obstructions to the liquid
flow, was constructed from the original packing elements
as follows:-

The original element was unwound to give a
continuous ribbon of multifil mesh which was then carefully
folded in a zig-zag manner so as to form a set of parallel
vertical layers of mesh. The lengths of the individual
layers were varied so that the assembled mass was circular
in cross-section, its diameter being approximately six
inches The last 18 inches of the band was not folded in
this way, but was passed round the circumference of the
assembly so as to hold the parallel layers tightly together.
The resulting packing element was of fairly even density, in
particular there was no central region of high density.

5.

A two-feet depth of this packing (6 packing elements) was tested in the six-inches diameter distillation column.

(iii) <u>Results of Distillation Tests</u>

Using a Total Reflux Rate of 550-600 lb/hr. the H.E.T.P. values of the two modifications were as follows.

Cone-Shaped Packing H.E.T.P. = 5.0 inches

Parallel Vertical Packing H.E.T.P. = 2.2 inches

The original KnitMesh packing gave an H.E.T.P. of 2.8 inches undersimilar conditions (cf. F.T.S.R., Dec. 1960, p.17). The Cone-Shaped packing was therefore an unsatisfactory modification, but the Parallel Vertical Packing, whose H.E.T.P. value was about 25% less than that of the original KnitMesh, was thought to be a promising packing arrangement.

The next section describes more detailed tests of this modified packing.

(c) <u>Testing of the Parallel Vertical Packing</u>

(1) <u>Tests with 4 ft. 6 ins depth of Hand-Made Packing</u>

Previous work had shown that the performance of the
original KnitMesh packing deteriorates with increase of
packed depth. The first investigation of the performance
of the Parallel Vertical modification was therefore
designed to establish the effect of an increase in the
packing depth.

Sufficient elements to fill the five-foot long
six-inches diameter column section were constructed by
hand. The four foot six inches depth of packing was
tested in the distillation column over a range of total
Reflux rate from 185 to 620 $lb/hr.ft^2$.

(2) <u>Tests with Factory-Made Packing</u> - <u>Distillation at Atmospheric Pressure</u>.

The results of part (1), see above and Table 1 p 9,
showed that the improved performance of the Parallel
Vertical packing observed with a two-foot depth of
packing was maintained with a five-feet depth. The
hand-made packing elements are imperfect in construction,
and for the purposes of detailed testing of the modification
a supply of accurately assembled elements was obtained from
KnitMesh Ltd. These factory-made elements were constructed
in a slightly different way from the hand-made packing.
Instead of assembling an element from a continuous folded
ribbon of knitted mesh, each layer of the factory-made
variety was an individual length of ribbon, cut to the
appropriate size, such that a more accurately circular
cross section resulted from the assembly of the several
lengths of ribbon. The parallel lengths of mesh were again
enclosed in a circumferential band of mesh.

A depth of 4 ft. 6 ins of the packing was tested
at total reflux and at atmospheric pressure in the six-
inches diameter distillation column. In the tests the
H.E.T.P. and pressure drop of the packing were measured

using the system Methylcyclohexane-Toluene. Boil-up rates
in the range 100 to 1000 lb/hr.ft^2 were employed.

The pressure drop across the packing was measured
by a water manometer connected to nitrogen bleeds to the top
and bottom of the column.

The majority of these runs were performed with a
well distributed reflux to the top of the packing. In a
number of runs, however, the reflux was fed to the packing
as two concentrated central streams. This arrangement was
intended to investigate the effect of the initial distribution
of liquid on the packing performance.

(3) **Tests with Factory Made Packing - Distillation at 200 mm Hg. Abs.**

Using the same packing as in (2) above a number of
runs were performed at a pressure of 200 mm. Hg. Absolute.
These runs were intended to give an indication of the perfor-
mance under vacuum of the parallel vertical packing.

(4) **Distribution Measurements with Parallel Vertical Packing**

The distillation runs with the hand-made and factory-
made Parallel Vertical packing both showed an increase of
H.E.T.P. with reflux-rate. (See below, p 10). It was
though that this increase might be the result of a deterioration
of the liquid distribution with increasing liquid rate.
A number of distribution measurements were therefore performed
in the six-inches diameter distribution column (see F.T.S.R.
October 1959). The hand-made and the factory-made packings
were tested as follows.

(i) A depth of 4 ft 6 ins of the hand-made backing
was tested with a well-distributed feed of Gas Oil . Total
flow rates in the range 100-550 lb/hr.ft^2 were used.

(ii) With the factory-made mesh - (a) with a 4 ft.
6 ins. packing depth the variation of liquid distribution
with total liquid rate was investigated, using a distributed
source of Gas Oil,

(b) the distributions with a contral point food
and with a distributed food wore compared;

(c) the variation of the liquid distribution with
depth of packing was moasured, using a distributed source
of constant flow rate oqual to 400 lb.por $hr.ft^2$.

(5) Results

(a) Hand-Made Mesh

H.E.T.P. values at a number of Boil-Up rates are shown in Table 1, and are plotted on Graph 2. (Back of this report).

Boil-Up Rate lb./hr.ft^2	Number of Theoretical Plates	H.E.T.P inches
143	27	1.9
185	25	2.15
270	23	2.35
420	15	3.6
560	13.2	4.1
620	11.6	4.65

Table 1   Distillation Performance of Hand-Made Parallel Vertical Packing

Table 1 shows that at low boil-up rates the performance of the packing is excellent, but that the H.E.T.P. increases with boil-up rate. However, in the range of boil-up rates investigated the H.E.T.P. is always less than that of the original KnitMesh Packing. (The H.E.T.P. of the spirally-wound packing was 5-6 inches over the whole range of reflux rates.)

The variation in liquid distribution with variation in liquid rate is discussed below.

(b) Factory-Made Mesh   Distillation at Atmospheric Pressure and at 200 mm Abs. Pressure

The results of all the distillation tests are given in Table 2.

The following graphs were constructed from Table 2.

Graph 1 - the variation of H.E.T.P. with vapour velocity.

Graph 2 - the variation of H.E.T.P. with boil-up rate. Graph 2 includes the results for the hand-made Parallel Vertical packing, taken from Table 1.

Graph 3 - the variation of pressure drop with $\sqrt{p}$. This is the Reed and Fenske pressure drop correlation which has been widely applied to randomly-packed columns.

(c.f. Reed and Fenske. Ind.Eng.Chem., 42, 659 (1950)).

Graph 4 - the variation of pressure drop per theoretical

plate with vapour velocity. The pressure-drop per

theoretical plate has been proposed by Ellis and Varjavandi

(c.f. Chem. and Proc.Eng. 7, 293 1958) as a suitable

parameter for comparing high-efficiency packing.

Run	Boil Up Rate lb./hr.ft^2	Number of Theoretical Plates	H.E.T.P. inches	P mm. H_2O	P per T.P. mm. H_2O	Vapour Velocity V ft/sec.	$V/\bar{\rho}$
A	**760 m.. Pressure Distributed Feed.**						
1	165	26	2.1	-	-	0.234	0.104
2	295	22	2.45	1	0.046	0.419	0.186
3	329	18.5	2.9	2	0.11	0.466	0.207
4	386	21.5	2.5	3	0.12	0.547	0.243
5	482	15.6	3.45	6	0.38	0.684	0.303
6	580	15.4	3.5	8.5	0.55	0.822	0.365
7	640	14.0	3.9	13	0.95	0.908	0.403
8	652	14.0	3.9	11	C.86	0.925	0.410
9	742	12.9	4.2	15	1.17	1.025	0.467
10	880	11.5	4.7	-	-	1.248	0.555
11	960	10.4	5.2	-	-	1.369	0.607
12	1080	9.6	5.6	61	6.3	1.530	0.680
B	**760 mm. Pressure. Point Feeds at Centre.**						
13	390	20	2.7			0.554	0.246
14	595	14.8	3.65			0.844	0.374
15	833	12.9	4.2			1.180	0.525
C	**200 mm. Pressure**						
16	242	20	2.7	15	0.75	1.308	0.297
17	351	12.5	4.25	21	1.7	1.895	0.431
18	394	10.1	5.35	24	2.4	2.125	0.481
19	592	7.7	7.0	40	9.2	2.927	0.665

Table 2   Distillation Performance of Factory-Made Parallel Vertical Packing

11.

Graph 2 shows that the factory-made packing is superior
to the hand-made packing. The H.E.T.P. of the former
increases less rapidly with increasing reflux rate than
does that of the latter. However, the fall of efficiency
with increasing reflux-rate is still sufficiently marked
to be a disadvantage of the Parallel Vertical packing.
Graph 3 shows that the pressure drop through the packing
at reduced pressure cannot be correlated by the Reed
and Fenske factor. Work by Varjavandi (Ph.D. thesis,
University of Birmingham, 1959) on two-inches diameter
KnitMesh packing resulted in the same conclusion. There
is at present no satisfactory method of correlating
and predicting the pressure drop in knitted mesh packings.

The pressure drop per theoretical plate (see Graph 4)
is lower at the reduced pressure, and on the basis of
this criterion it can be predicted that the modified
packing will be suitable for distillation under vacuum.

(C) Distribution Measurements

Graph V shows the liquid distribution obtained
with the hand-made Parallel Vertical Mesh.

Graph 5 shows the distribution with the factory-
made mesh.

Both graphs show that a wall-effect - ie. a concen-
tration of liquid flow on the column wall- is present
in the modified packing. The main difference between the
hand-made and the factory-made packings is that in the
former packing the liquid flow increases progressively
towards the wall, and the wall effect becomes more marked
with increasing liquid rate whilst for the factory-made
mesh most of the liquid running down the wall appears
to be drawn from the packing adjacent to the wall, and
the wall-effect is not significantly affected by the
liquid rate. The liquid distribution in the central
regions of the packing is more even in the factory-made
packing. This improvement in the distribution in the

facory-made mosh may oxplain its gonorally bettor distillation porformanco, but tho incroaso in H.E.^{T}.P. with roflux rato cannot bo simply oxplainod in torms of tho liquid distribution.

Graph 5(D) shows that tho final liquid distribution is not much influonced by tho ovon distribution or othorwiso, of tho food . This fact probably oxplainod tho similarity botwoon tho H.E.T.P. valuos obtainod with a point roflux to thoso obtainod with a distributod roflux (Soo Graph 2). It should not bo nocossary to provido an olaborato distributing plato in ordor to obtain tho bost distillation porformanco of tho modifiod packing.

(D) Modifications to tho Parallol Vortical Packing

It was thought to bo of intorost to tost a numbor of difforont arrangomonts of parallorl vortical moshos. Firstly, it may bo possiblo to produco a choapor typo of packing by using mono-filamont mosh togothor with tho multi-filamont mosh. Tho low-donsity mono-filamont mosh could bo usod to spaco apart tho layors of multi-filamont mosh which woro tho principal surfacos on which mass-transfor was taking placo. Socondly it has boon obsorvod that if tho vortical mosh is rotatod through 90°, so that tho axis of tho ribbon of mosh is vortical, tho sproad of liquid ovor tho mosh surfaco is groator, and tho aroa for mass transfor to or from tho mosh is thus oxpoctod . to be incroasod. The uso of parallol layors of mosh makos the assembly of a packing oloment incorporating these modifications possiblo. A spirally-wound mosh is much loss suitable for such modifications.

At the timo of writing two modifiod parallol, vortical packing arrangomonts havo boon tostod in tho

six-inches diameter distillation column.

(1) Alternate layers of uncrimped multifil and crimped mono-filament copper mesh. A two-feet depth of packing was tested.

(2) Parallel Vertical multifilament mesh with the axes of the mesh ribbon parallel to the column axis. Since the long sides of the mesh are parallel to the column axis the packing elements were most conveniently made in lengths greater than the four inches of the original modification. The column was loaded with five elements each one foot in length.

Both of these sub-modifications were tested and a number of boil-up rates, and a consistent value of H.E.T.P$\frac{1}{2}$ of about 10 ins was obtained for both packings at all reflux rates. Neither of these sub-modifications was satisfactory.

(E) <u>Tests in a 2 inches square Column</u>

A small column was constructed for the purpose of testing on a small-scale further modifications to the packing. Modifications can be more cheaply and more quickly assembled on a small scale.

The column consists of a 2 inches square x 24 inches long brass section in which the packing is mounted. One side of the brass case can be removed for loading the packing. The brass section is connected to a glass reboiler and a condenser. Liquid sample points are provided at the top and bottom of the column, and there is a reflux meter between the column and the reboiler.

The column has been used to test the performance of the following packing arrangements made up from the original KnitMesh ribbon:-

(1) four inches long elements of parallel packing identical to the type tested in the six inches diameter column.

(2) Two-inches cube elements in which the layers

of mesh were horizontal.

(3) Four inches long elements similar to (1)
above but in which 5-strand wires were used instead of
8-strand wires. Graph 7 shows the variation of the H.E.T.P.
values of these three packings with boil-up rate at total
reflux and also the H.E.T.P. values for the parallel mesh '
packing in the 6 inches diameter column. Graph 8 shows
the corresponding pressure drop in these packings.

It will be seen from Graph 7 that the H.E.T.P. values
of the 8 strand packings in the 2 inches column are less
than those in the 6 inches column. The "diameter effect",
whereby the H.E.T.P. of the packing increases with column
diameter, is still present in the modified packings, although
its magnitude has been considerably reduced, especially
at low boil-up rates.

The 5 strand mesh was found to be somewhat less
efficient than the 8 strand meshes, probably because of the
smaller mass transfer area which the 5 strand mesh provides,
but the 5 strand packing is of interest in view of its lower
cost and reduced pressure drop. Its performance under high
vaccuum,. where its low pressure drop is of particular
importance, is at present being investigated.

The high efficiency of the horizontal packing
arrangement in the 2 inches column was unexpected. The
large difference from the performance of this packing in
a 6 inches column is not understood. The advantage of the
high efficiency of this packing over a wide boil-up range
is to some extent off-set by the higher pressure drop
which the packing was found to produce and by the difficulty
of making up the packing for small diameter columns.

(F) <u>Discussion of Results</u>

The Parallel Vertical Mesh Packing has distillation
and liquid distribution properties which are superior

to tho original, spirally-wound, KnitMosh packing. In
Graph 6 the porformance of tho modifiod packing is comparod
with that of a numbor of othor high-officioncy packings.
Tho data plottod in Graph 6 was obtainod at atmosphoric
prossuro in six-inchos diamotor columns.

Tho packings choson for comparison woro

(1) Stodman Packing (Stodman. Cn.J.Rosoarch, B15 383 (1937))

(2) McMahon Packing (McMahon, Ind.Eng.Chom., 39, 712 (1947))

(3) Borad Rings (Ellis and Goodwin, Ind.Chomist, 37, 436,
(1961)

The H.E.T.P. valuos of tho Parallol Mosh packing
aro soon from Graph 6 to bo highor than thoso of tho bost

............continucd.

packing (Stodman), but they are nevertheless within the range of the best packings which have so far been devised.

The low H.E.T.P. values at boil-up rates of 200 lb/hr.ft^2 and less may indicate that the packing will be suitable for use under reduced pressures. The maximum boil-up rates under vacuum are less than those at atmospheric pressures owing to the higher vapour velocity which promotes flooding at much lower liquid rates. At pressures below about 100 mm Hg. the maximum reflux rate will not exceed 200 lb/hr.ft^2. Graph 2 shows that the H.E.T.P. values of the packing at 200 mm and at atmospheric pressures are similar at low boil-up rates below 200 lb./hr.ft^2.

The main advantage of the Parallel Vertical packing is seen to lie in its low pressure-drop per theoretical plate, as shown in Graph 6. At boil-up rates below 800 lb.per hr.ft.^{2} the packing gives the lowest values of this factor of any of the packings compared.

It will be seen from Graph 6 that in general low H.E.T.P. value is obtained at the expense of a high pressure-drop, but at low reflux rates the Parallel vertical packing combines a low pressure-drop with H.E.T.P. values which are only one half to two-thirds those of Berad Rings, which are the only other packing having a low pressure-drop. The Parallel Vertical packing is thus the most suitable packing when a low pressure-drop is essential.

As mentioned above, and as can be seen from Graph 6, the main disadvantage of the modified packing is the increase of its H.E.T.P. with increasing reflux rate. This increase cannot be readily explained in terms of the liquid distribution properties of the packing.

A possible explanation is the decrease in contact
time between the liquid and vapourphases as the vapour
velocity increases. The change in vapour velocity
cannot, however, be the only factor which determines
the change in H.E.T.P. values. This is shown by Graph 1
where the H.E.T.P. at a given vapour velocity is less
at 200 mm pressure that at atmospheric pressure. Further-
more, as Graph 6 shows, the H.E.T.P. values of the
Parallel Mesh packing increase more rapidly with reflux
rate tha.. do those of the other high-efficiency packings,
whereas the effect of increasing vapour velocity would
be expected to be similar.

It is possible that the liquid hold-up also has
an effect on the H.E.T.P. values. At the reduced pressure
the liquid hold-up and the liquid flow-rate for a given
vapour velocity are less than those at atmospheric
pressure, and a closer approach to equilibrium between
the vapour and liquid phases is possible.

(9) Conclusions

(1) By replacing the spirally-wound arrangement
of the original KnitMesh packing by an arrangement in
which the layers of mesh are vertical and parallel
to each other, a packing having improved distillation
efficiency is obtained.

(2) This modified packing has H.E.T.P. values in
the range 2-5 inches in a six-inches diameter column, as
compared to 5-6 inches for the original KnitMesh.

(3) The modified packing has a low pressure drop,
and for reflux rates below 800 lb/hr.ft^2 its pressure
drop per theoretical plate is lower than any other
high-efficiency packing which has been used in columns
of large diameter.

(4) Both tho H.E.T.P. valuo and tho proosuro drop
of tho packing incroaso with roflux rato, and at high
ratos tho paôking is loss satisfactory than a numbor of
othor high-offioioncy packings.

(5) No satisfactory oxplanation can at prosont
bo givon for this dotorioration of tho porformanco of
tho packing with incroasing liquid rato. It cannot bo
adoquatoly oxplainod in torms of tho liquid distribution
proportios of tho packing.

(6) Tho uso of parallol layors of mosh onablos
packing olomonts which aro not circular in cross-soction
to bo moro oasily constructod.

PART 3   THEORETICAL WORK

(A) Introduction

Tho aims of thb theoretical work havo boon doscribod in tho Final Tochnicpl Status Roport of Docombor 1960. This roport doscribe# tho dorivation of tho oquation

$$\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2} = \frac{1}{D_L} \frac{\partial M}{\partial z} \tag{1}$$

for liquid sproad in a randomly-packod column (Soo p 26 for tho moasuring of tho symbols usod in this soction).

In tho majority of randomly-packod columns thoro is a moro or loss sorious "wall-offoct" - io. concontration of liquid flow on tho column wall. Any adoquato thooroticaI prodiction of tho liquid distribution in a packod column must tako this wall-offoct into account.

Provious attompts to prodict tho liquid distribution (soo Tour and Lohiman,   Trans.Am.Inst.Chom.Eng., 35 719 (1939) and Cihla and Schmidt,   Coll.Czoch.Chom.Comm., 22, 896 (1957) and 23, 569 (1958)) aro unsatisfactory in that thoy do not tako into account tho wall offoct.

Bolow wo doscribo a solution of oquation (1), abovo, in which an attompt is mado to allow for tho wall-offoct. Tho solution contains two paramamators which havo to bo dotorminod oxporimontally, and mothods aro suggostod for thoir ovaluation.

(B) Solution of tho Liquid Sproad Equation with Wall-Effoct.

For a circular column oquation (1) is writton in polar co-ordinatos.

$$\frac{\partial M}{\partial z} = D_L \cdot \frac{1}{r} \frac{\partial}{\partial r} \left(r \cdot \frac{\partial M}{\partial r} \right) \tag{2}$$

The boundary conditions for the solution of equation 2 are obtained from consideration of the physical requirements for the irrigation of a packed column.

The column is of limited radius $\underline{a}$, at which radius the "diffusing" liquid meets the column wall. It is known that a proportion of the liquid reaching the wall is returned to the packing, whilst the rest remains on the wall. There is no⊾ evidence that the whole of the liquid reaching the wall is retained by the wall. If the whole were retained by the wall, then, in a column of sufficient length, there would be a negligible proportion of the liquid remaining in the packing. It is frequently observed that after a sufficient depth of packing the rates of liquid on the wall and in the body of the packing attain constant values.

In order to adequately explain the behaviour of the wall if must be considered as acting neither as a perfect reflector of liquid nor as a perfect sink of liquid. It is assumed in the present treatment that the wall behaves in such a way that the flow rate per unit area in the packing adjacent to the wall, $\underline{M(a,z)}$, is proportional to the total flow rate on the wall, $\underline{W(z)}$

$$\text{ie} \quad M(a,z) = K \ W(z) \tag{3}$$

where K is a constant, which is referred to as the Wall Co-efficient.

At any depth $\underline{z}$ below the top of the packing the flow rate from the packing to the wall is

$$- D_L \ 2 \pi a \left(\frac{\partial M(r,z)}{\partial r} \right) r = a$$

The value of $\underline{W(z)}$ at any depth $\underline{z}$ is the sum of all the liquid which has flowed to the wall above $\underline{z}$.

ie
$$W(z) = - 2 \pi a\, D_L \int_{z\,min}^{z} \left(\frac{\partial M(r,z)}{\partial r} \right)_{r=a} dz \qquad (4)$$

where $\underline{z\ min}$ is the depth below the top of the packing at which liquid first appears at the wall.

Eliminating $\underline{W(z)}$ by means of $\underline{3}$ the boundary condition

$$M(a,z) = - 2 \pi a\, K.D_L \int_{zmin}^{z} \left(\frac{\partial M(r,z)}{\partial r} \right)_{r=a} dz \qquad (5)$$

is obtained.

The initial condition is determined by the nature of the liquid feed to the column. Equation $\underline{2}$ can only be used with axially symmetrical sources. The most common case is that of a distributed source. If an ideal distributed source is assumed the initial condition can be represented by the equation

$$M(r,0) = f^{0} \quad \text{for } 0 \leqslant r \leqslant a \qquad (6)$$

The total liquid rate to the column is then $\pi a^2\, f^0$. For the distributed source $z\ min = 0$, and $W(0) = 0$, and $\underline{5}$ becomes

$$M(a,z) = 2 \pi\cdot aDK \int_{0}^{z} \left(\frac{\partial M(r,z)}{\partial r} \right)_{r=a} dz = 0 \qquad (7)$$

A third boundary condition is that of symmetry of the flow profile about the column axis. This is expressed as

$$\left(\frac{\partial M(r,z)}{\partial r} \right)_{r=0} = 0 \qquad (8)$$

Using equations $\underline{6}$, $\underline{7}$ and $\underline{8}$ equation $\underline{2}$ was solved by the method outlined below.

It is known that equation $\underline{2}$ has a solution of the form

$$M(r,z) = \sum_{n=1}^{\infty} e^{-q_n^2 \left(\frac{D_L z}{a^2}\right)} \left[A \, J_0\left(\frac{q_n r}{a}\right) + B \, Y_0\left(\frac{q_n r}{a}\right) \right]$$

but the boundary condition $\underline{9}$ cannot be conveniently used with this solution. The equation $\underline{2}$ was therefore solved by making a number of substitutions.

(1) $\phi(r,z) = M(r,z) - f^0$ (9)

(2) $y(r,z) = 2\pi \int_0^r r.\phi(r.z)dr$ (10)

(3) $y(r,z) = \psi(r,z) - \left(\frac{f^0 r^2}{K}\right) \div \left(a^2 + \frac{1}{\pi K}\right)$ (11)

The final solution in terms of $\psi(r,z)$, is then

$$\psi(r,z) = -\sum_{n=1}^{\infty} \frac{8 a \, f^0}{K(a^2 + 1/\pi K)} \left(\frac{1+\alpha}{q_n(\alpha^2 q_n^2 + 4\alpha + 4)}\right) \times$$

$$\frac{r \, J_1\left(\frac{q_n r}{a}\right)}{J_0(q_n)} \exp -q_n^2 \left(\frac{D_L z}{a^2}\right) \qquad (12)$$

where $\alpha = 1/\pi a^2 K$ (13)

and q_n is defined by the equation

$$2 \, J_1(q_n) + \alpha q_n \, J_0(q_n) = 0 \qquad (14)$$

The solution in terms of $M(r,z)$, found by substituting back from equations $\underline{9}$, $\underline{10}$ and $\underline{11}$ into equation $\underline{12}$ is

$$M(r,z) = \left(\frac{\alpha}{\alpha+1}\right) f^0 - 4\alpha f^0 \sum_{n=1}^{\infty}\left(\frac{1}{\alpha^2 q_n^2 + 4\alpha + 4}\right) \times$$

$$\frac{J_0\left(\frac{q_n r}{a}\right)}{J_0(q_n)} \exp -q_n^2 \left(\frac{D_L z}{a^2}\right) \qquad (15)$$

From $\underline{15}$ the liquid flow rate per unit area at any point (r,z) in the column can be computed in terms of the initial uniform distributed flow rate per unit area, $\underline{f^0}$.

The calculation of $M(r,z)$ involves the knowledge of the two parameters D_L, the liquid spread co-efficient, and K, the wall coefficient (which appears as a factor in   ).

(C) Determination of the Parameters D_L and K

The values of the parameter D_L and K depend upon the physical conditions in the packed column. The precise factors upon which D_L and K depend cannot be stated until they have been determined under a number of conditions, but it is likely that D_L depends upon the type and size of packing and K upon the type and size of packing and the ratio of packing size to column diameter.

D_L and K can be determined experimentally using a packed column which has provision for collecting the liquid running from it in a number of concentric annular vessels of known radii.

D can only be determined independantly of K in a column operating with no wall-effect. This condition is best obtained by feeding a small area or "point" source of radius $\underline{b}$ to the top of the packing with its centre at the column axis. If the height of the packing, $\underline{z}'$ is so adjusted that the liquid just reaches the outer collecting annulus, whose inside radius is $\underline{c}$, then the boundary conditions for use with equation $\underline{2}$ are, are,

$$M(r,0) = f^o \quad \text{for} \quad 0 \leqslant r \leqslant b \qquad (16)$$

$$M(r,0) = 0 \quad \text{for} \quad b < r \leqslant c \qquad (17)$$

$$M(c,z) = 0 \qquad (18)$$

The solution to $\underline{2}$ obtained with these boundary conditions is

$$M(r,z) = 2 \, f^o \left(\frac{b}{c}\right) \sum_{n=1}^{\infty} \left(\frac{J_1\left(\frac{q_n b}{c}\right)}{q_n \left[J_1(q_n)\right]^2} \right) J_o\left(\frac{q_n r}{c}\right) \exp - q_n^2 \left(\frac{D_L z}{c^2}\right)$$

$$\cdot \, - \qquad\qquad (19)$$

where $J_0 (q_n) = 0$ (20)

From 19 the proportion of the total flow rate ($= \pi b^2 f^o$) appearing at a depth z' within a radius d ($< c$) of an inner collecting vessel is evaluated as

$$P\left(\frac{d}{c}\right) = 4 \left(\frac{d}{b}\right) \sum_{n=1}^{\infty} \frac{J_1\left(\frac{q_n b}{c}\right) J_1\left(\frac{q_n d}{c}\right)}{q_n^2 \left[J_1(q_n)\right]^2} \exp{-q_n^2 \left(\frac{D_L z'}{c^2}\right)} \quad (21)$$

The R.S. of equation 21 is calculated for a number of values of $(D_L z'/c^2)$ and the values plotted. From the graph the value of $(D_L z'/c^2)$ corresponding to the experimentally determined value of the L.S. of 21 is determined, and hence D_L is evaluated.

K can be determined independantly of D_L by use of equation 15 when z is large Equation 15 predicts that at infinite packing depth the flow rate attains the radially independant value of $(\alpha/\alpha +1)$ times the feed rate per unit area. The depth of packing is increased until this equilibrium rate is approximated to. The flow rates per unit area in all but the outer collecting annulus of the distribution column should then be approximately the same. It is unlikely that there rates will be exactly similar owing to channeling and to the uneven arrangement of the packing elements resting on the collecting vessels. An average of the several values should be taken. If this average flow rate in the pack is denoted by f_∞ we have

$$f_\infty = (\alpha/\alpha +1)f^o$$

whence $K = \left(\frac{f_o - f_\infty}{f_\infty}\right) \frac{1}{\pi a^2}$ (22)

(D) Experimental Testing of the Liquid Spread Equation

The six inches diameter distribution column was
modified for the purpose of testing the liquid spread
equation. The concentric ring collecting pot was replaced
by a honeycomb plate containing 125 hexagonal collecting
pots by means of which a more detailed observation of the
radial variation of the liquid flow rate could be made.

The liquid running to each of the 125 pots from
the packing was collected in rows of measuring vessels.
The radial variation of the liquid flow rate was determined
by taking the average rate of sets of pots situated at
the same radial distance from the centre of the honeycomb.

The liquid distribution produced by $\frac{1}{2}$" Ceramic
Rashig Rings in the six inches diameter column was studied.
First, the values of D_L and K for use in equation 19 were
determined by the methods indicated on pp. 22 and 23.
Equation 19 was then used to calculate the variation of
$M(r.z)$ with r for a number of values of z up to 12 feet.
The calculated variations were compared with the corresponding
experiment of variations. It was found that there was
a large scatter of the experimental points and that no
significant comparison of the predicted and experimental
radial variations could be made.

A more detailed experimental study was then made
of the liquid distribution produced by 6 inches and 12
inches packed depths. 20 mms. were performed at each
depth. After each run the packing was removed from the
column and reloaded in order to alter the random arrangement
of the layer of rings resting on the collecting pots, which
arrangement has been found to effect the measured liquid
distribution.

(b) The average radial variation of the liquid flow rate
was compared with the corresponding predicted variation.
It was found that the experimental and predicted variations
were in broad agreement. In particular the predicted
sharp fall in the liquid rate in the zone of packing
adjacent to the wall was confirmed. However, the theoretical
flow on the wall was found to be somewhat higher than the
experimental value.

The experimental points, based on the average of
20 runs were again considerably scattered. The standard
deviations of the means of the 20 runs were of the order
of 50% of the means themselves, so that no detailed
conclusions could be drawn from the experimental study.
The scatter of the experimental points is thought to arise
partly from channeling of liquid running through the
packing. The effect of channeling is difficult to predict
theoretically, and the possibility of channeling occurring,
must always be an objection to a simple theory of liquid
distrib. tion.

The scatter of points in the experimental liquid
distribution experiments must throw doubt on some of the
published liquid distribution measurements and may explain
the contradictory results which are reported.

(E) Extension of the Theoretical Work to Mass Transfer in
Packed Columns

One method of estimating the mass transfer
in a packed column, starting with the Liquid Spread equation,
was outlined in the F.T.S.R. of December 1960 (see p. 21).

A second method, using Dimensionless Analysis, is being considered. The performance of a column is known to depend on a large number of operating variables. The most important variables are thought to be

(1) the Liquid Rate, $\underline{L}$

(2) the Vapour Rate, $\underline{G}$

(3) the Mean Slope of the equilibrium curve $\underline{m}$

(4) the Type and Size of packing, hence D_L

(5) the Depth of Packing, z

(6) the Column Diameter, $\underline{2a}$

(7) the Wall Co-efficient, $\underline{K}$

(8) the Liquid and Vapour phase Mass Transfer Coefficients, $\underline{k_L}$ and $\underline{k_G}$.

The ratio of the ideal H.T.U., to that obtained with evenly distributed liquid and vapour phases, which can be predicted by standard methods, to the actual H.T.U., can be expressed by a dimensionless equation of the form

$$\frac{\text{H.T.U. ideal}}{\text{H.T.U. actual}} = fn\left[\frac{mG}{L} \; ; \; \frac{D_L z}{a^2} \; ; \; \frac{k_L}{k_G} \; ; \; \alpha \; ; \; \dots \right]$$

A dimensionless equation of this kind suggests a number of experiments which would be performed to determine the effect of the groups appearing on the R.S. of the equation.

At present consideration is being given to the type of apparatus suitable for the experiments suggested.

26.

(F) <u>List of Symbols used in Part 3</u>

a   radius of column

b   radius of "point" source

c   radius of collecting annulus

d   radius of another collecting annulus

f° distributed food rate per unit area

f_{∞} liquid flow   rate per unit area at infinite
                                                    depth

q_n parameter in solutions of equation $\underline{2}$

r   radial variable

$y(r,z)$ liquid flow function defined by equation $\underline{10}$

z   linear variable (packing depth)

z' depth below food at which liquid first appears
            in outer collecting vessel.

z min   depth below food at which by liquid first appears
                at column wall.

D_L liquid spread co-efficient

K   wall co-efficient

A, B,   constants in solution of equation $\underline{2}$

M   liquid flow rate per unit area in the packing

$W(z)$ liquid flow rate on the column wall

Jo, J_1 Bessel Functions of the First Kind

Yo   Bessel Function of the Second Kind

α $= 1/\pi a^2 K$ cf equation $\underline{13}$

$\phi(r,z)$ function defined by equation $\underline{9}$

$\psi(r,z)$ function defined by equation $\underline{11}$
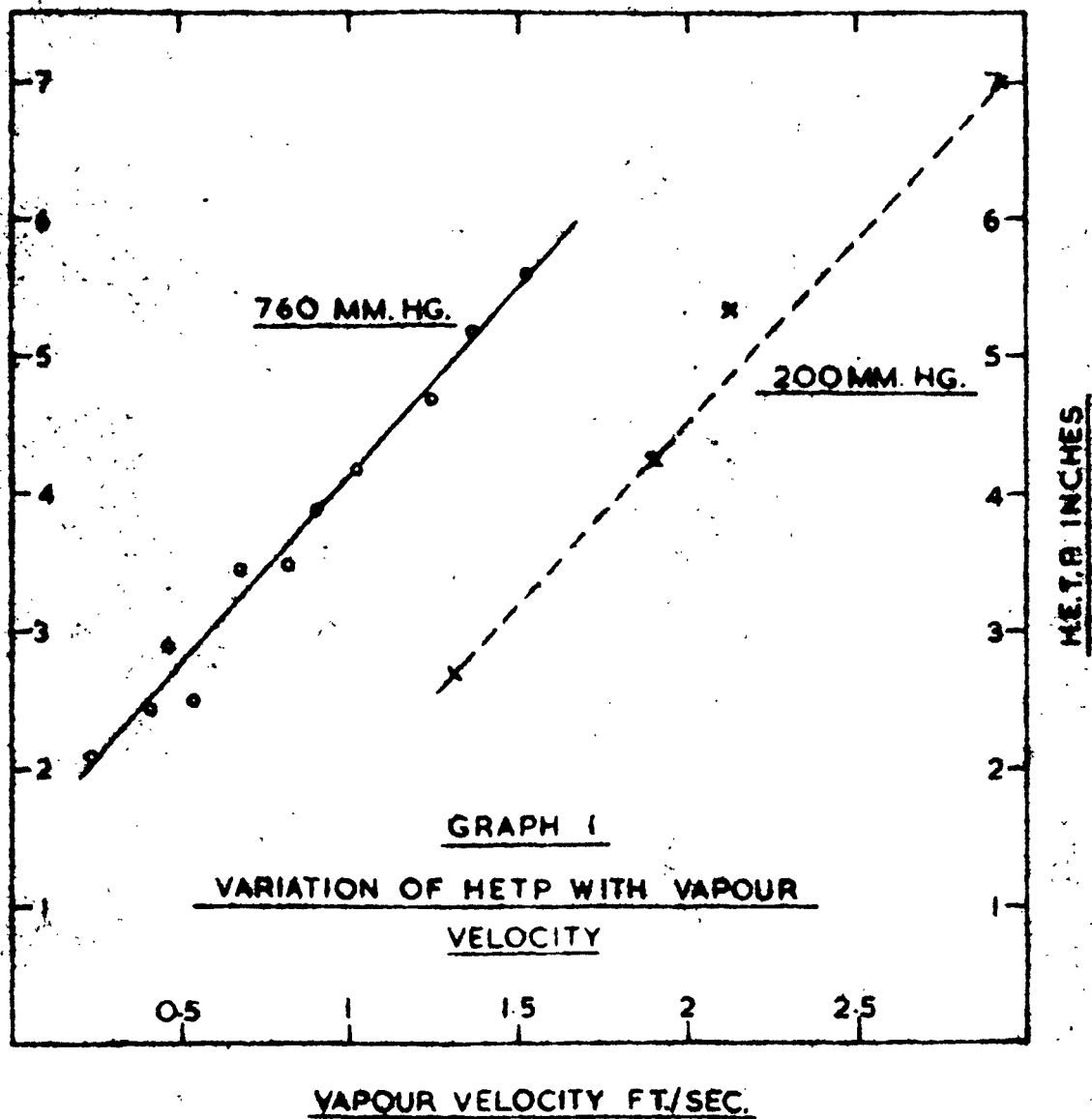
(4) FUTURE WORK

It is hoped that work will continue in the Department on improving the performance of the Parallel Vertical modified packing.
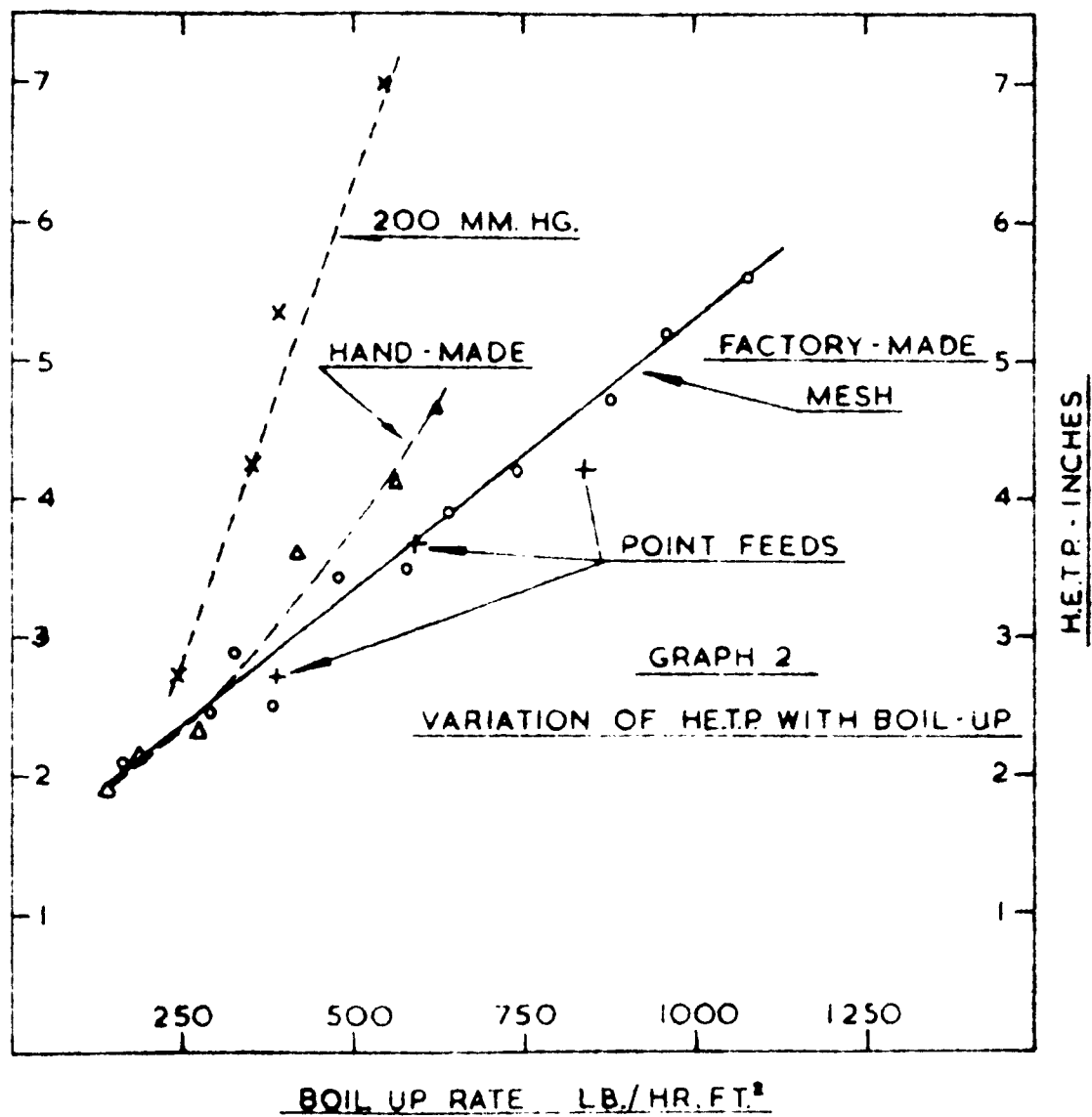
When the six-inches diameter distribution column has been reconstructed it is hoped that more detailed liquid spread measurements for various packings will provide further information on the performance characteristics of these packings.

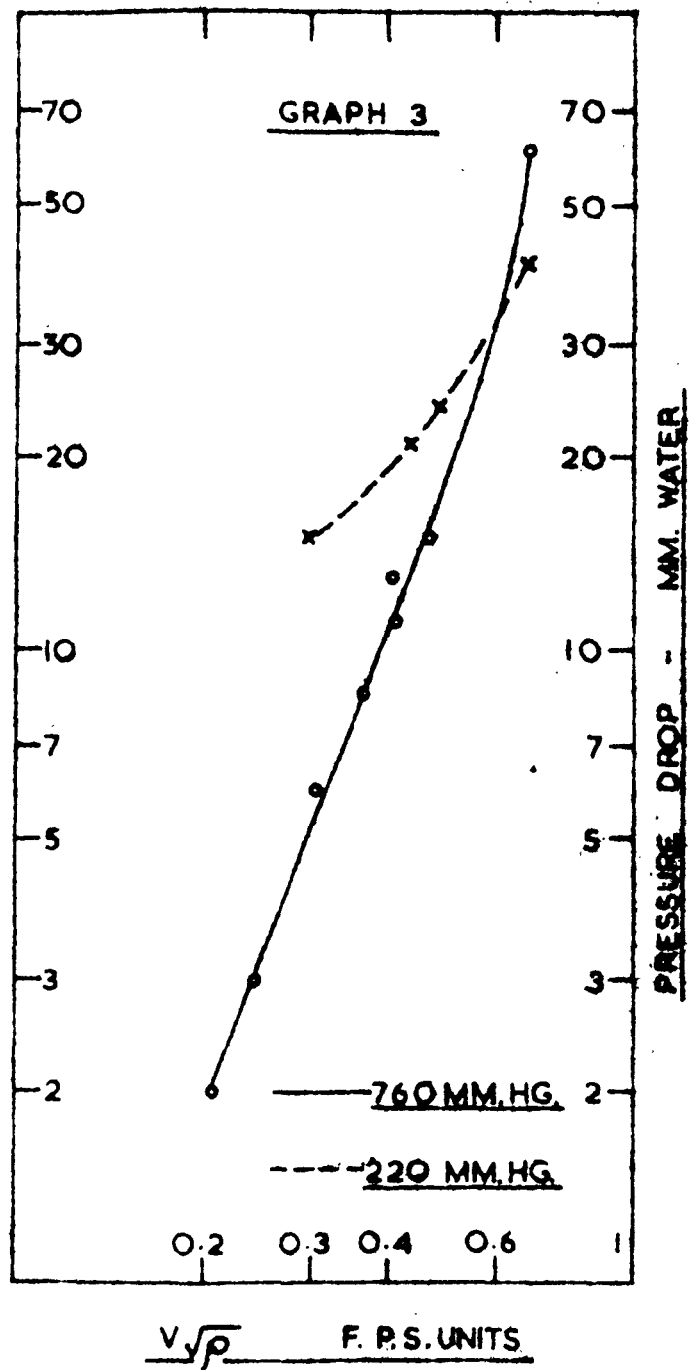Research work is likely to continue on pressure drop measurement at pressures of 1-10 mms Hg.

It is hoped that the predictions of the Liquid Spread equation will be further tested in the modified distribution column, and values of the parameter D_L and K determined for a number of packings.

760 MM. HG.

200 MM. HG.

H.E.T.P. INCHES

GRAPH 1

VARIATION OF HETP WITH VAPOUR
VELOCITY

VAPOUR VELOCITY FT./SEC.

200 MM. HG.

HAND-MADE

FACTORY-MADE
MESH

POINT FEEDS

GRAPH 2

VARIATION OF H.E.T.P WITH BOIL-UP

H.E.T.P. INCHES

BOIL UP RATE LB./HR. FT.²

GRAPH 3

VARIATION OF ΔP WITH V√ρ

GRAPH 4

VARIATION OF PRESSURE

DROP WITH

VAPOUR VELOCITY

PARALLEL MESH
PACKING

——————— 760 MM. HG.

- - - - - - 200 MM. HG.

VAPOUR VELOCITY   FT. PER SEC.

PRESSURE DROP PER THEORETICAL PLATE – MM. WATER

8 5 3 2 1 0.7 0.5 0.3 0.2

0.3 0.4 0.8 1.0 2 3 4

GRAPH 5

MEAN POSITION OF COLLECTING VESSEL

FLOW PER UNIT AREA AS A PROPORTION OF THAT IN THE CENTRAL CHANNEL

Explanation of Graph 5

<u>Graph 5A.</u> Distributed Feed. Variation of Distribution
                                   with Total Liquid Rate

☉----------☉ - 200 lb/hr.ft^2.

+————————+ - 450 lb/hr.ft^2.

X——————————X - 720 lb/hr.ft^2.

<u>Graph 5B</u> Distributed Feed. Variation of Distribution
                                  with Depth of Packing

+——————————+ - One Packing Section (= 4 inches)

☉——————————☉ - 3 Packing Sections

X----------X - 6   "   "

△—————————△ -15   "   "

Total flow rate = 400 lb./hr.ft^2.

<u>Graph 5C</u> Central Point Source. Variation of Distribution
                                       with Depth of Packin

X——————————X - One Packing Section

☉----------☉ - 3 Packing Sections

+—————————+ -15   "   "

Total flow rate = 550 lb./hr.ft^2.

<u>Graph 5D</u> Comparison of Distributions
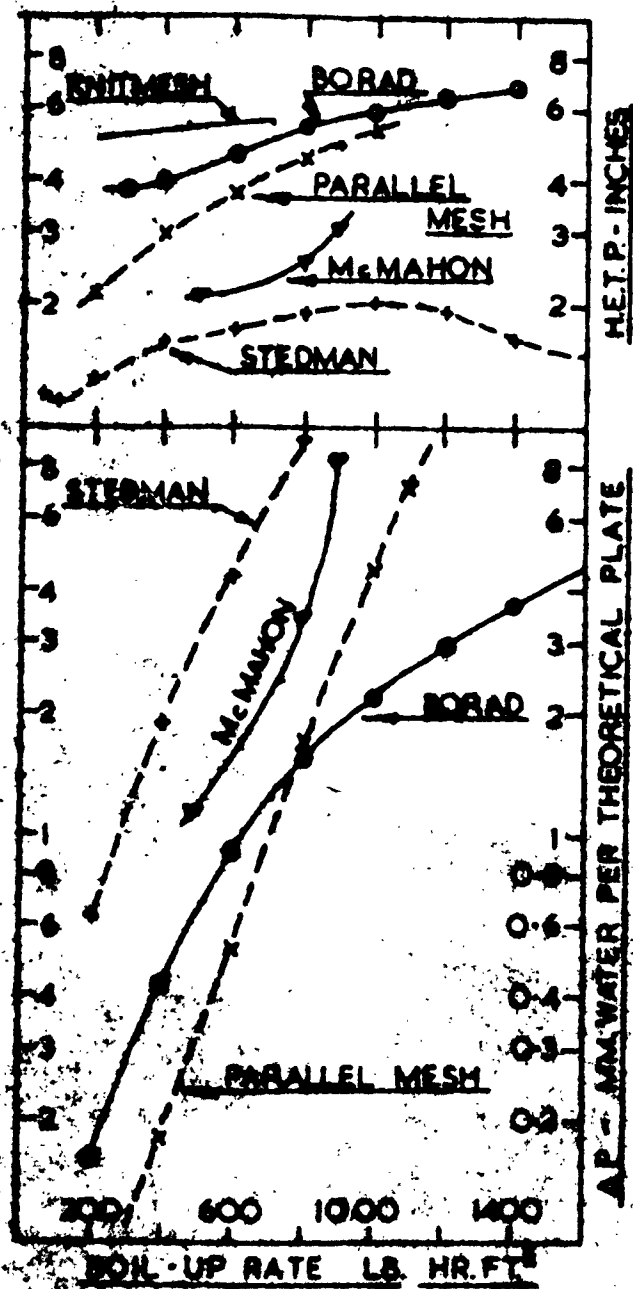
X——————————X - Hand-Made Mesh

☉----------☉ - Factory-Made Mesh, Distributed Feed

+—————————+ -   "   "   "   Point Feed.

GRAPH V

VARIATION OF DISTRIBUTION
WITH TOTAL LIQUID RATE.
PARALLEL MESH PACKING.
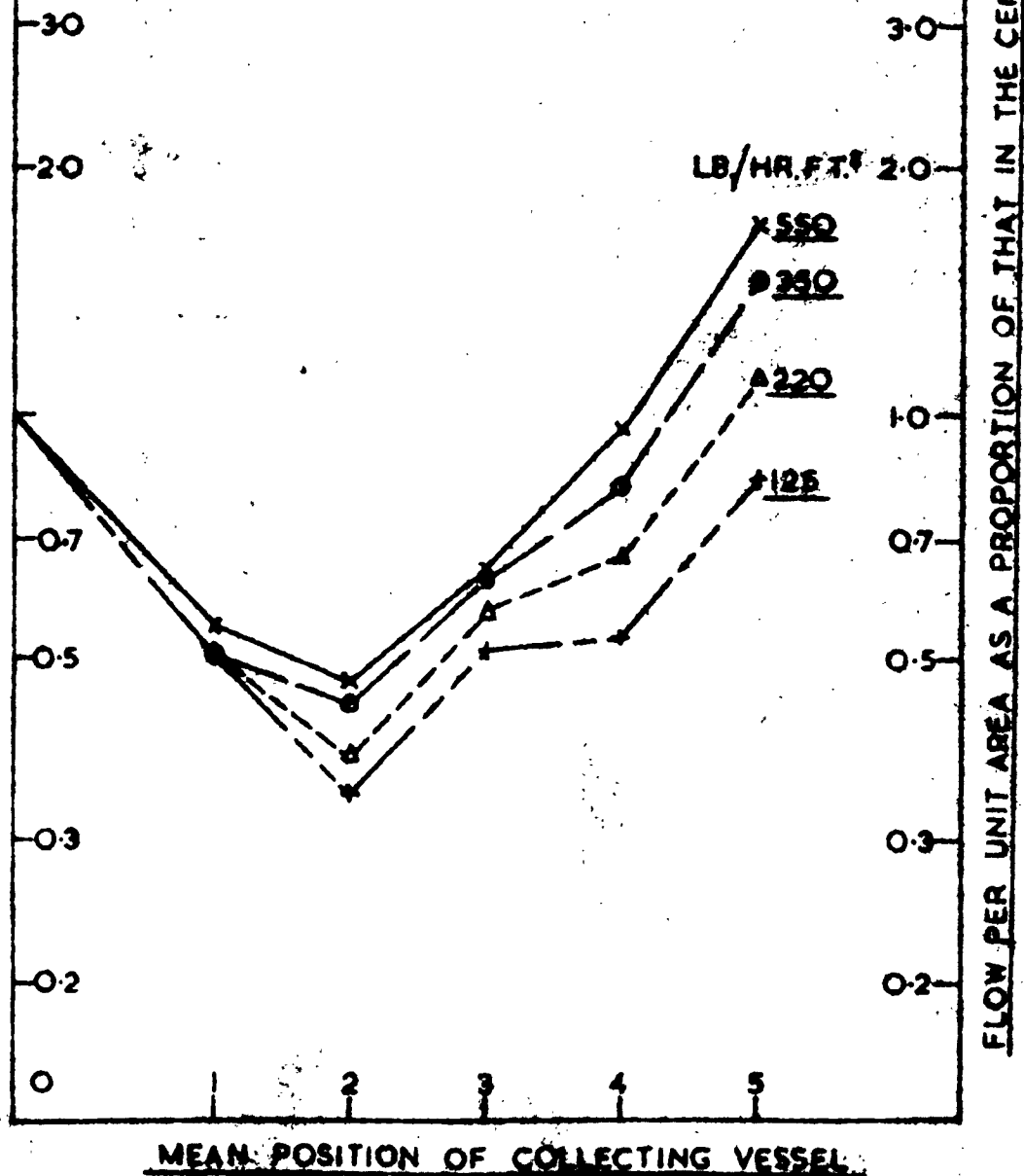
GRAPH 6

COMPARISON OF HIGH EFFICIENCY

PACKINGS IN 6 INCHES DIA.

COLUMNS

GRAPH 7

COMPARISON OF PACKINGS IN
2 INCHES SQUARE COLUMN
AND IN 6 INCHES DIA. COLUMN

5 strand

Parallel Mesh
in 6"dia. Columh

Parallel Mesh
in 2"sqr. Column

8 strand

Horizontal Layers
in 2"sqr. Column

H.E.T.P. INCHES

BOIL-UP RATE. LB./HR. FT.²

PRESSURE DROP. CM. WATER / CM.

Horizontal
Layers

8 strand

5 strand

Parallel Mesh in
6" Column

GRAPH 8

PRESSURE DROP VALUES IN THE
2 AND 6 INCHES COLUMNS

BOIL-UP RATE. LB./ HR.FT.²